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Space-charge spectroscopy of self-assembled quantum dots InAs in GaAs

N. V. Bazlov†, *O. F. Vyvenko*†, O. A. Trofimov†,
A. Yu. Egorov‡, A. R. Kovsh‡, V. M. Ustinov‡ and A. E. Zhukov‡
† Insitute of Physics of St. Peterburg State University,
198904 St. Petersburg, Russia
‡ Ioffe Physico-Technical Institute RAS,
194021 St. Petersburg, Russia

Abstract. Semiconducting structure containing the planes of self assembled InAs quantum dots (QD) in the GaAs matrix are studied by means of junction space charge spectroscopy methods. The effects associated with low temperature GaAs covering layer, with the wetting layer (WL) and with QDs itself are separated. It is found that DLTS signal in the structures with the high density of the QD exhibits not usual properties. A new model is proposed that takes into account the electron capture from the free electron "lake" arising due to a large repulsive barrier of the QD planes.

1 Introduction

At the present the electronic properties of semiconducting structures containing self-assembled quantum dots (QD) are studying intensively both theoretically and experimentally. A satisfactory agreement was found between the theory and experimental data obtained by means of the optical spectroscopy methods [1]. Recently, junction space charge spectroscopy, such as capacitance voltage profiling (CV) [3] and deep level transient spectroscopy (DLTS) [2, 4] was used for the measurements of semiconducting structures with QD. It was found that the shape and other properties of the DLTS peaks distinguished noticeably from the ones due to usual point-like defects as well as due to quantum well structures [5]. The peculiarities observed does not allowed to get an unambiguous information about the electron transitions between the local energy states of QD and semiconductors bands.

In this work we present the results of our investigation of InAs/GaAs QD by means of CV, DLTS, as well as admittance spectroscopy (AS) and optical DLTS (ODLTS). We propose a new explanation of the origin of the capacitance transients in the Schottky-diodes with the plane of a high QD density.

2 Samples

The structures studied were grown on (100) Si-doped GaAs substrates by solid-source molecular beam epitaxy (MBE) in Riber 32P apparatus using As4 species and atomic fluxes of indium and gallium. Silicon was used for n-type doping. All structures were grown under standard for MBE condition of enrichment by group V element (As). After annealing of substrate in growth chamber at 620 °C during 10 minutes the 0.2 μm layer of GaAs with high level of Si-doping was deposited. The next 0.8 μm layer slightly doped with silicon contained 10 nm of undoped GaAs. The structures under investigation differed by amount of InAs deposited in the middle of undoped layer and contained 4, 1.7 and 1 monolayer (ML) of InAs, and the last sample contained no InAs insertion. The substrate temperature was 485 °C for the deposition of InAs and 10 nm GaAs covering layer to exclude effects of In segregation and reevaporation and 600 °C for the rest of the structure. In the case of the sample without InAs the substrate temperature also decrease to 485 °C at deposition of 10 nm GaAs. According to the data of transmission electron microscopy, 1 ML of InAs is equivalent the wetting layer (WL) thickness (i.e. no quantum dots), whereas 1.7 ML is sufficient to form quantum dots (QDs), (i.e., QDs on WL). Thus, having such set of the samples the effects associated with low temperature GaAs covering layer, WL, and, finally, with QDs itself can be separated.

CV-profiles of net-donor concentration, N_D, AS, DLTS and ODLTS spectra were measured on the Schottky-diodes preparing by evaporating of the gold contacts on the top of the structures in the temperature ranges between 80 and 350 K.

3 Results

The diodes without InAs ($Q = 0$) layer showed only a week step on CV-profiles correspondent to lowering of the net-donor density which is believed due to non-doped GaAs-layer. Introducing InAs leads to the appearance an apparent peak of the N_D that at the room temperature increased with the increasing the depth of the InAs layer indicating the presence of the acceptor-like levels lying below the shallow donor level.

The samples with $Q = 0$ and $Q = 1$ do not show any signal during the measurements of AS, DLTS and ODLTS. AS measurements on the samples with $Q = 1.7$ reveal a peak of the HF-conductance and a step of the capacitance at a temperature of 85 K at the testing voltage frequency $\nu = 1$ MHz. The energy activation of the thermoemission of electrons from apparent level of about 80±20 meV was estimated from the Arrenius-plot data obtained by the variation of ν from 1 to 10 MHz.

DLTS signal in a wide temperature region was detected in the samples with $Q = 4$. The shape of the spectrum changes dramatically when the applied bias changes. At at a forward or at a sufficiently low reverse voltage bias DLTS spectrum with a low temperature peak QD and high temperature peaks HT (Fig. 1) was registered. When the reverse bias voltage was increased the spectrum consisted of subsequential positive and negative peaks similar to the reported in [4] that should be ascribed to the emission from electron and hole traps respectively. It was found that QD-peak decreased with the decreasing filling pulse amplitude, U_p, with the appearance threshold of about 0.3–0.4 eV whereas HT peak remained constant up to, $U_p = 0.05$ V. That allows to separate the peaks by appropriate sequences of U_p (Fig. 1) during DLTS experiment. The activation energies of the apparent emission proccess were found to be 0.33 ± 0.02 eV for QD peak and to be in the ranges from 0.4 to 0.6 eV for HT peak depending on the condition of the experiment. The amplitude of the QD does not whereas that of HT peak strongly depended on the temperature. Both peaks had similar logarithmic dependence on the refilling pulse duration that indicates the electron capture limiting with a occupancy dependent barrier.

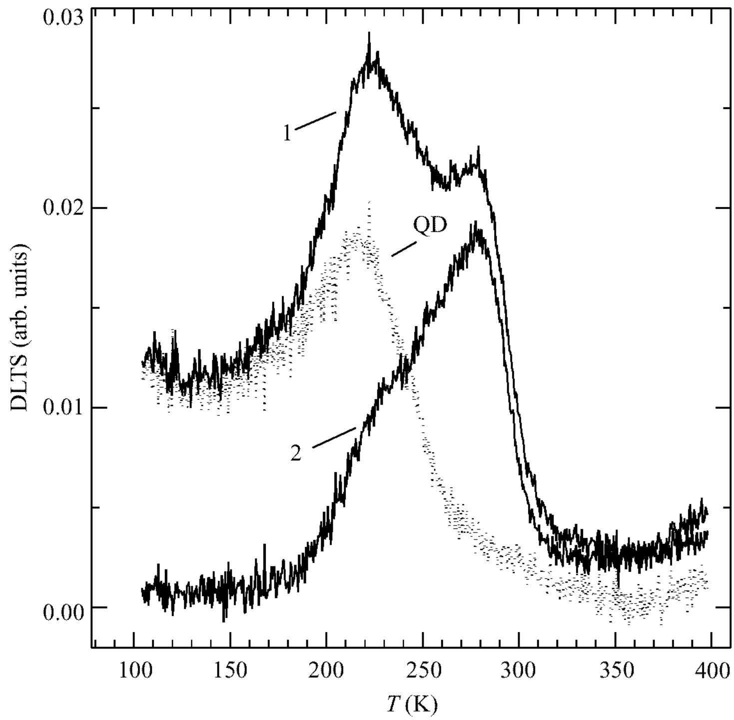

Fig 1. DLTS-Spectra on the sample QD-4ML as measured in a single tempreature scan. $U_p =$ 1–2.5 V, 2–0.5 V. $U_b = 0$ V. Dotted line is the difference bettween lines 1 and 2.

4 Discussion

The properties of the DLTS-peak QD are in accordance with the usual theory of the thermoemission from the traps except the low temperature tail of the signal, that was previously reported in [2] for the InP QD and may be due to the direct tunneling of the electrons from the QD states. That is why we ascribe QD-peak to the electron confined states of the InAs/GaAs quantum dots. The activation energy of the QD-peak agrees well with the theoretical calculations for the QD with a base diameter of 14 nm.

To explain other peculiarities of the DLTS signal in the samples with a high density of quantum dots we propose the model of the free carriers capture limited relaxation as follows. The plane with the QD when filled with electrons builds a large repulsive barrier for the electrons like the electronic states of grain boundaries in semiconductors [6]. During the filling voltage pulses not only the electron occupancy of the QD-levels but also the free electron density in the conduction band between the QD-plane and metallic contact increase because of the local minimum of the electrostatic potential. in between. In this way an electron "lake" will be created just after switching off the filling pulses. During the emission phase of the DLTS experiment the electron emission from the QD levels occurs in the presence of the electron current from the "lake" flowing through the QD plane. The rate of the QD states occupancy relaxation will be then defined as a sum of the electron emission and the electron capture rates and will be sooner than the rate of the relaxation of the free electron density in the "lake". That is why the kinetic of the QD states occupancy will follow the kinetic of the time changes of the free electron density in the "lake". The latter is defined by the barrier that decreases with increasing of the voltage bias applied to the diode.

Detailed analysis of the model including mathematical treatment of the problem that will be presented at the conference allows to explain all properties of DLTS spectra observed.

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